

SATELLITE TIME TRANSFER PAST AND PRESENT

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Abstract

An overview of past accomplishments is presented that shows the development of satellite time transfer techniques and capabilities that are used today. The development is traced from the concepts and early demonstrations using a single satellite to the global coverage now provided by a constellation of satellites. Predictions of future technology are compared with what has been accomplished over the last 25 years. Co-operative experiments performed jointly by colleagues of the PTTI Meetings were key to the development. These experiments demonstrated the potential of time transfer by satellites having global coverage. Some of the results are reviewed and compared to current capabilities.

INTRODUCTION

Time transfer by satellite began in the mid to late 1960s, and much of the initial work was performed by members of the Precise Time and Time Interval (PTTI) community and reported at the PTTI Systems and Applications Meetings. The following is an accounting of experiments published in past PTTI Proceedings that traces the development of satellite time transfer. It focuses on applications using passive ranging techniques with navigation satellites and in particular the development of time transfer via the Global Positioning System. One other passive ranging satellite navigation system should be mentioned. The Navy Navigation Satellite System (NNSS), also known as TRANSIT, was a low-altitude Doppler system that provided time transfers on the order of 10-50 microseconds of accuracy [8]. There were also efforts that used synchronous communications satellites for two-way time transfer. Applications of two-way time transfer have matured in their own right and are considered a different method. The methods and experiments described begin with the Navy TIMATION satellites, continue with the Navy Navigation Technology Satellites (NTS), and conclude the DoD Global Positioning System (GPS) satellites.

TIMATION

The first experiment to be described was reported in the 3rd PTTI Proceedings of December 1971 [1, 2]. The methods used required a substantial manual effort, as microcomputers and even electronic calculators were in their infancy. The TIMATION satellites (Figure 1) were in 500-nautical-mile orbits and transmitted a series of tones from 100 Hz to 100 kHz. Receivers used these tones for measuring the propagation range from the satellite to the user. The clocks onboard the satellites were derived from stable crystal oscillators designed by Frequency Electronics, Inc. The method of time transfer was based on a celestial navigation technique that was developed by the French naval officer Marcq St. Hilaire in the mid 1800s. The new method replaced the stars with satellites and star charts with pre-computed intercept charts. The

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pre-computed intercept chart (Figure 2) had an assumed position of the navigator in the center of a circle with a scaled radius equal to the uncertainty in the position. Predicted range lines to the satellite were drawn for each minute of observation through the center assumed position. The range lines were determined *a priori* using satellite positions calculated from predicted orbits. For altitudes of the TIMATION satellites, a typical pass lasted about 15 minutes. Observations were made for each predicted line and the measured ranges to the satellite were plotted as perpendicular lines on the corresponding prediction, as shown in Figure 3. If the navigator's clock and the satellite clock are perfectly synchronized, then the plotted lines intersect at the true position of the navigator. If the clocks are not synchronized, then the lines formed an arc with a radius equal to the time difference of the two clocks (Figure 3). By making a similar measurement at another location, the clock offsets relative to the same satellite can be compared and a time transfer between two ground clocks obtained. The accuracy of the system was originally classified, but has since been declassified and released as shown in Figure 4. This early experiment demonstrated time transfers with an accuracy of 113-125 nanoseconds over continental distances [3].

An experiment that demonstrated sub-microsecond time transfer over global distances was conducted during 1972-1973 and reported in the 5th PTTI Proceedings of December 1973 [4]. Time transfers were performed using the TIMATION II satellite between the Naval Research Laboratory (NRL) in Washington, DC, and the Royal Greenwich Observatory (RGO) in England. Time transfers were also performed between the Naval Research Laboratory and the Defense National Mapping (DNM) Agency in Australia. The method used treated the satellite clock like a portable clock being transported in orbit. When the satellite passed over each ground station, a time difference between the satellite clock and the ground station clock was measured. The measurements were passed to the central control station at NRL through a satellite-linked computer system for time transfer processing. The time transfer equation shown in Figure 5 is the same as that used today. It is in terms of the measured or observed range, O_{obs} , where the difference between the satellite clock and ground clock is $t_{sat}-t_g$, the theoretical predicted range is t_{prop} , the delays due to the ionosphere and troposphere are Δt_{iono} and Δt_{trop} , the calibration delay is K , and ϵ is the uncertainty error in the measurement. The frequency of the satellite clock relative to the NRL reference clock was maintained at the central control station at NRL. The measurements taken at each ground station were differenced and corrected for the satellite clock frequency offset to get the difference of the ground stations relative to the reference clock at NRL. The time transfer data from DNM Australia showed 110-370 nanoseconds rms and that of RGO England was 600 nanoseconds rms (Figure 6).

NAVIGATION TECHNOLOGY SATELLITES (NTS)

By 1974 navigation and timekeeping by satellite was beginning to be noticed. The news strip, "Our New Age," shown in Figure 7, predicted timekeeping to within a billionth of a second and supersonic aircraft positioning to within 1000 feet. The Navigation Technology Satellites, launched and operated from 1974 to 1979, were at higher altitudes that provided a longer measurement interval, 8-hour orbit for NTS-1 and 12-hour orbit for NTS-2 (Figure 8). Each satellite flew atomic frequency standards, rubidium on NTS-1 and cesium on NTS-2. Global time transfer experiments were conducted using NTS-1 that demonstrated an improved accuracy over the TIMATION satellites [5]. NTS-2 was the first GPS test satellite and was launched into the same orbit as is currently used today. NTS-2 also carried the first GPS pseudo-random noise (PRN) code modulated signal package. The accuracy of the cesium on NTS-2 allowed for verification of the theory of relativity as applied to clocks in space.

During 1975-1976 NASA Goddard Space Flight Center (GSFC) funded a joint effort by NRL, Naval Surface Weapons Center Dahlgren Laboratory, and Johns Hopkins Applied Physics Laboratory to design a satellite time transfer receiver to support their earth crystal dynamics program. The receiver was designed to work with the newer experimental Navigation Technology Satellites developed by the Naval Research Laboratory. The receiver was an analog signal design with data processing and operator interface pro-

vided by an Intel 8080 microprocessor. An early lesson learned, which is still experienced today, was the susceptibility of low-level satellite signals to interference by common RF sources. During the receiver testing at Dahlgren, Virginia, an interference was experienced that disabled operation of the receiver. Over the course of an investigation it was noticed that the interference began around 8:00 am and ceased around 5:00 pm. A car was instrumented with a spectrum analyzer and high gain antenna then driven around the area in an attempt to locate the source. The direction of the source always appeared to be in the direction of the antenna of the receiver under test. Finally, a multi-purpose radio was used to demodulate the interfering signal that was found to be a Washington, DC, broadcast FM station. The IF of an FM receiver located in a penthouse next to the test receiver antenna was interfering with the down-converted satellite signal.

The first field demonstration test of the receiver was performed at the NASA GSFC tracking station in Rosman, North Carolina (Figure 9). The test was performed over a two-week period in November 1976, and the results were published in the 8th PTTI Proceedings of November 1976 [6]. An example satellite observation for NRL and Rosman are shown in Figure 10. The time transfer measurement for each satellite pass was taken at the time of closest approach (TCA) of the satellite to the ground station in order to minimize orbit prediction error as well as the effects of the ionosphere. The data results plotted over the period of the test show an rms of 86 nanoseconds. Portable clock measurements were used as a truth comparison reference and were taken at the beginning and end of the test. Figure 10 shows that the portable clock measurements agree well with the satellite measurements.

During 1978-1979 a co-operative International time transfer experiment was performed between eleven organizations in eight countries using the newly designed receivers with the NTS satellites (Figure 11). The results of this experiment were published in the 10th and 11th PTTI Proceedings of November 1978 and November 1979 [7, 9]. The time transfer process was getting better, but still required a significant manual effort (Figure 12). The NTS transmitted signal power required a receiver antenna with significant gain. A yagi antenna design provided the gain (~15 dB), but had to be manually steered once a minute to maintain synchronization with the satellite as it passed overhead. A satellite signal generator was used to test the instrumentation setup after installation before attempting live tracks. With only two satellites available for time transfer measurements, the coverage usually meant a significant amount of tracking times occurred during non-working hours. Hence, the addition of punch-paper-tape for recording the data and an electrical timer used to schedule operation of the punch-tape device coincident with the satellite passes. This would allow the equipment to operate automatically in the absence of field personnel. It worked great until the introduction of European 50-cycle power to the U.S.-made 60-cycle line synchronous timer. This caused a loss in data before the start-stop intervals were scaled by 5/6 to account for the difference in line power frequency. After the data were collected, an analyst downloaded the satellite orbit predictions and reference station measurements from the NRL central station via satellite-linked computers, and processed the new data into time transfer results. A portable clock was used to perform truth comparison measurements during the experiment. The resulting global time transfer data had rms deviations of 152-998 nanoseconds and agreed with the portable clock measurements to within 30-570 nanoseconds (Figures 13, 14).

NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)

A constellation of five GPS Block I satellites was on-orbit by 1981. Several efforts were underway to develop GPS time transfer receivers to take advantage of the new satellite technology. In the demonstration phase, GPS was broadcasting date, time, and satellite position data in the downlink signal. The constellation was synchronized to GPS system time and broadcast a predicted difference from the DoD Master Clock at USNO. The signal was powerful enough that receivers could use omni-directional antennas. Microprocessor technology had advanced to microcomputer technology and was being used in the new

receiver designs. One such design was the NRL GPS Time Transfer Receiver that used an off-the-shelf Intel 8086 based microcomputer complete with a dual 8-inch floppy disk for data storage on removable magnetic media (Figure 15). Although the receiver used discrete logic design and analog RF components, the satellite PRN transmission codes, data message decoding, and time measurement processing were completely software-controlled. Improvements and updates could be programmed in software and send out on floppy disks for installation in the field. Another design was that of the National Bureau of Standards (NBS), now the National Institute of Standards and Technology, which used microprocessor technology and a state-of-the-art designed and built-in precise time interval counter. Test results of both receivers were published in the 13th PTTI Proceedings of December 1981 [10, 11]. A field test of the NRL receiver performed time transfers between the Kennedy Space Center MILA facility in Florida and NRL in Washington, DC. This test used the method of one-way time transfer shown in Figure 16 [12]. Time measurements were made directly with the satellites and referenced to the DoD Master Clock at USNO by the broadcast prediction. The results of an example NAVSTAR 1 pass are shown in Figure 18. The data from a single satellite pass had an rms deviation of 11 nanoseconds and the data from all NAVSTARs had an rms deviation of 24-67 nanoseconds. Portable clock measurements were also performed and compared well with the satellite results. The NBS receiver test used the common-view time transfer method shown in Figure 17. Measurements are made simultaneously when in common view of a satellite and then differenced to obtain the time difference between the two ground stations. This method reduces the errors due to the uncertainty in satellite position as well as the delays due to ionosphere. The results shown in Figure 18 show that the uncertainty of a linear least-squares fit to the data was 2.2 nanoseconds.

REMOTE CALIBRATION AND TIME SYNCHRONIZATION (R-CATS)

Between 1978 and 1985, GPS launched and operated eleven Block I satellites. From 1981 to 1989 five to seven satellites were available for navigation and timing users. Time transfer applications using GPS had demonstrated nanosecond level accuracies, but often in practice, less accuracy was achieved. A major reason was the lack of performing and maintaining accurate GPS time transfer receiver system calibrations. In 1984 and 1985 NRL led a co-operative effort to perform a Remote Calibration and Time Synchronization (R-CATS) of six GPS time transfer stations at timing laboratories in five different countries (Figure 19). The results were published in the 17th PTTI Proceedings of December 1985 [13]. The effort included a direct calibration of components, verification of the GPS receiver antenna geodetic position, and a calibration using a side-by-side comparison of each subject receiver to a calibrated reference GPS receiver (Figures 20-21). For the calibration by comparison, a designated reference GPS time transfer receiver was taken to the reference station at USNO and compared side-by-side with the USNO GPS time transfer receiver. This same reference GPS receiver was then taken into the field and compared side-by-side with each of the other timing laboratory GPS time transfer receivers. At the conclusion of the calibration test, the reference receiver was again taken to USNO for comparison. The results in Figure 22 showed a 10-nanosecond closure agreement. Additional comparison measurements at USNO indicated the potential of 1-nanosecond calibrations and that the 10-nanosecond disagreement from the first comparison may have been due to a change in equipment delay. Station GPS receiver offsets were found to be from 10-30 nanoseconds, which demonstrated the need for periodic calibration of the GPS receiving equipment.

LINKED COMMON VIEW TIME TRANSFER (LCVTT)

By 1995 GPS was fully operational with a 24 constellation of newer Block II satellites. Time transfer using GPS was a well-accepted practice and NRL was using the GPS monitor station data to evaluate the performance of the GPS on-orbit clocks. The method of Linked Common View Time Transfer (LCVTT)

was developed by NRL to provide continuous measurements of each NAVSTAR clock relative to the DoD reference clock at USNO. This technique was published in the 27th PTTI Proceedings of December 1995 [14]. The method linked common-view measurements taken at different monitor station pairs to resolve each monitor station clock relative to the DoD Master Clock at USNO. These LCVTTs were in turn used with the individual satellite clock versus monitor station clock measurements to obtain the satellite clock versus DoD Master Clock. The method is described in Figure 23, where WAS represents the NIMA monitor station located at USNO and referenced to the DoD Master Clock. Using this method a closure of WAS compared to WAS via linked path was computed with a mean phase error of 31 picoseconds. The method was later extended to include multiple paths, which increased the amount of data by about ten percent, thus further reducing the system measurement noise (Figure 24). Results of this method were published in the 31st PTTI Proceedings of December 1999 [15].

SUMMARY

The development of time transfer by satellite has evolved into a major application of GPS. The international timing and standards laboratories around the world use it. Improvements over the years include a better GPS system time synchronization to the DoD Master Clock reference (Figure 25) and the availability of more satellites (Figure 26). The ease of use of satellite time transfer equipment has improved greatly since the first experimental units in the 1970s. The advancement in electronics technology has enabled the development of 12-channel receivers that simultaneously collect data from all satellites in view of the receiving station. Calibration of receivers remains a challenge that could be improved and standardized.

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	T-1	T-11
LAUNCH	5/31/67	8/30/69
ALT. (n.mi.)	500	500
INCL.	70°	70°
ECC.	.0008	.002
WT. (lbs)	85	125
POWER (W)	6	18
FREQ.	UHF	VHF / UHF
OSC.	Qtz	Qtz
$\Delta f/f$ (day)	300	100
pp10 ¹³		

Pre-computed Intercept Chart based on the Marcq St. Hilaire method of mid 1800's used in celestial navigation
Replace stars with Satellites

Center is assumed position
Circle represents magnitude of uncertainty
Lines represent predicted range to satellite

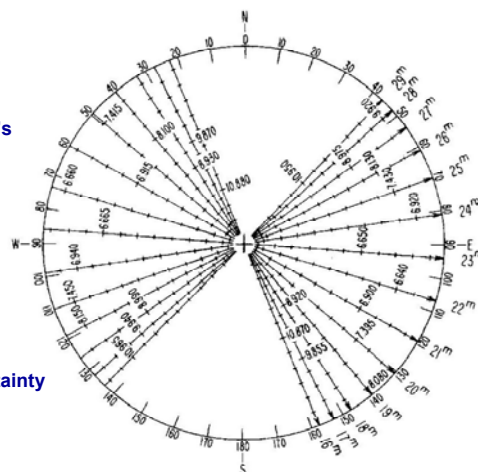
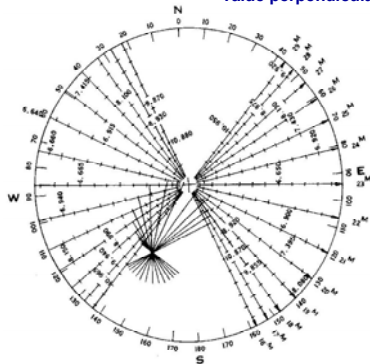


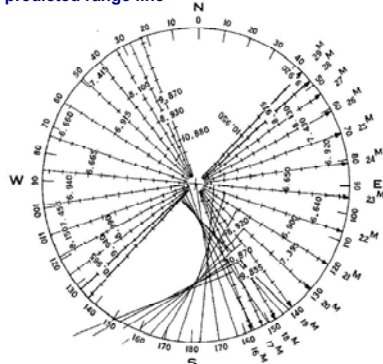
Figure 1. TIMATION Satellites 1967-1974

Figure 2. Time Transfer Method

Plot lines of position at measured range value perpendicular to predicted range line



Lines of position determine fix with zero time offset



Unknown clock offset is determined by radius of arc described by lines of position

Figure 3. Navigation and Time Solution

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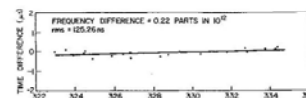


Fig. 7 (C) — Time comparisons between NRL and Florida obtained from TIMATION data

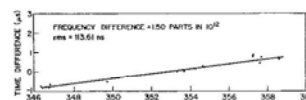


Fig. 8 (C) — Time comparisons between NRL and Colorado obtained from TIMATION data

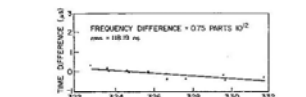


Fig. 9 (C) — Time comparisons between NRL and Alaska obtained from TIMATION data

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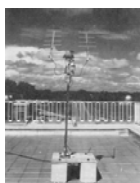
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Figure 4. Time Transfer Results



$$O_{obs} = t_{prop} + (t_{sat} - t_g) + \Delta t_{iono} + \Delta t_{trop} + K + \epsilon$$

Time Transfer Equation



Data link for predictions and measurements

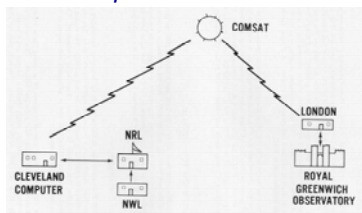


Figure 5. First Sub-microsecond Global Time Transfer by Satellite

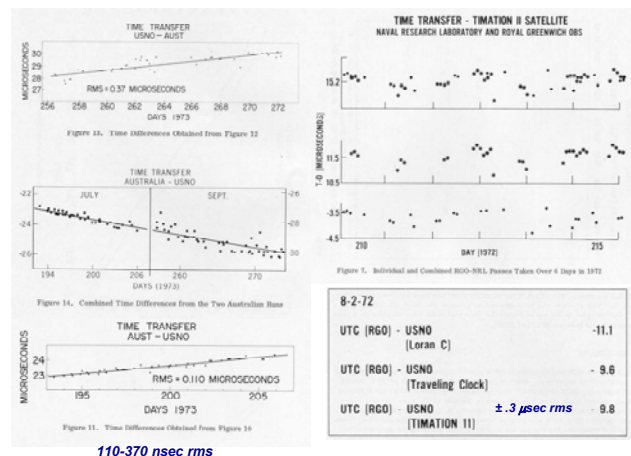


Figure 6. Global Time Transfer Results

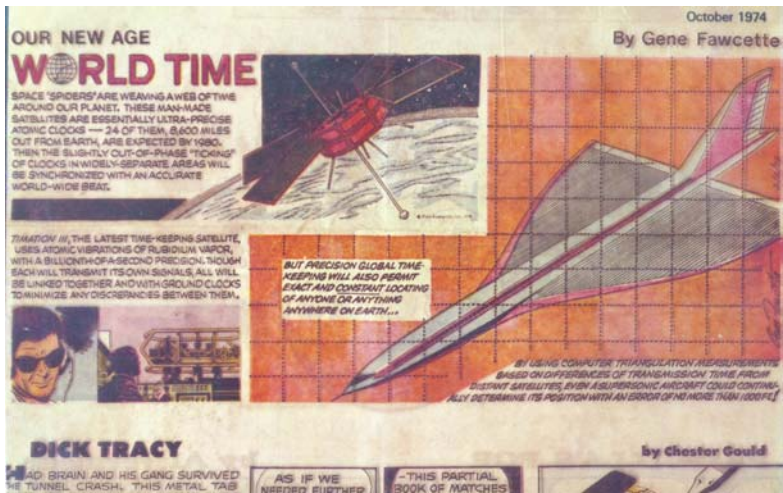
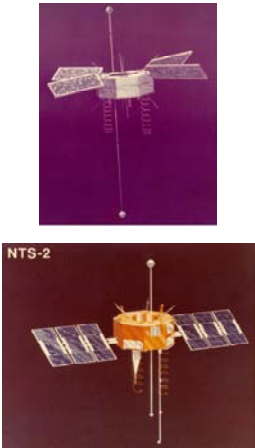


Figure 7. Forecast of the Future of Satellite Navigation and Timing



	NTS-1	NTS-2
LAUNCH	7/14/74	6/23/77
ALT. (n.mi.)	7400	10,900
INCL.	125°	63°
ECC.	.007	.0004
WT. (lbs)	650	950
POWER (W)	100	445 BOL
FREQ.	UHF / L BAND	UHF / L ₁ , L ₂
OSC.	Qtz / Rb	Qtz / C _s
$\Delta f/f$ (day) pp10 ¹³	5-10	2

Figure 8. Navigation Technology Satellites (NTS)

Analog signal design
Microprocessor controlled

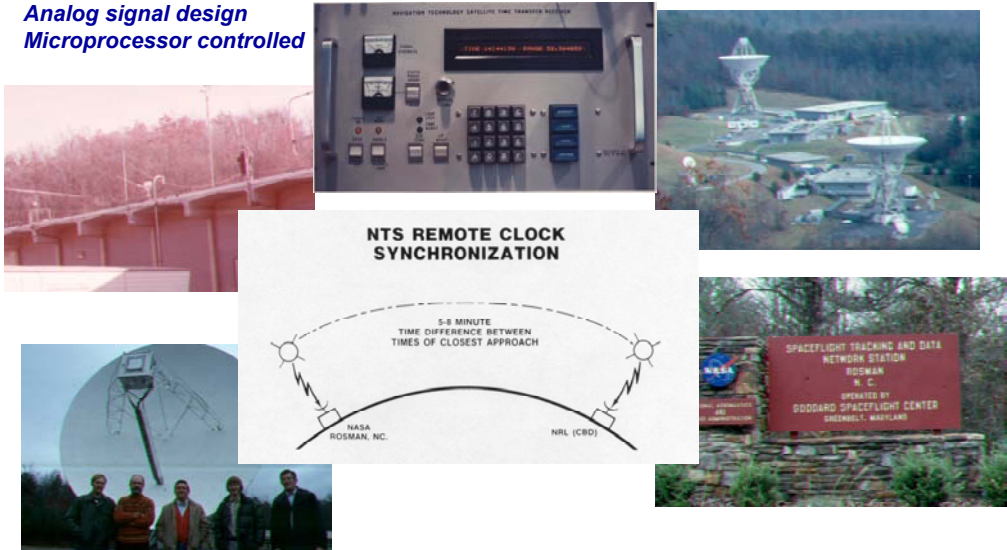
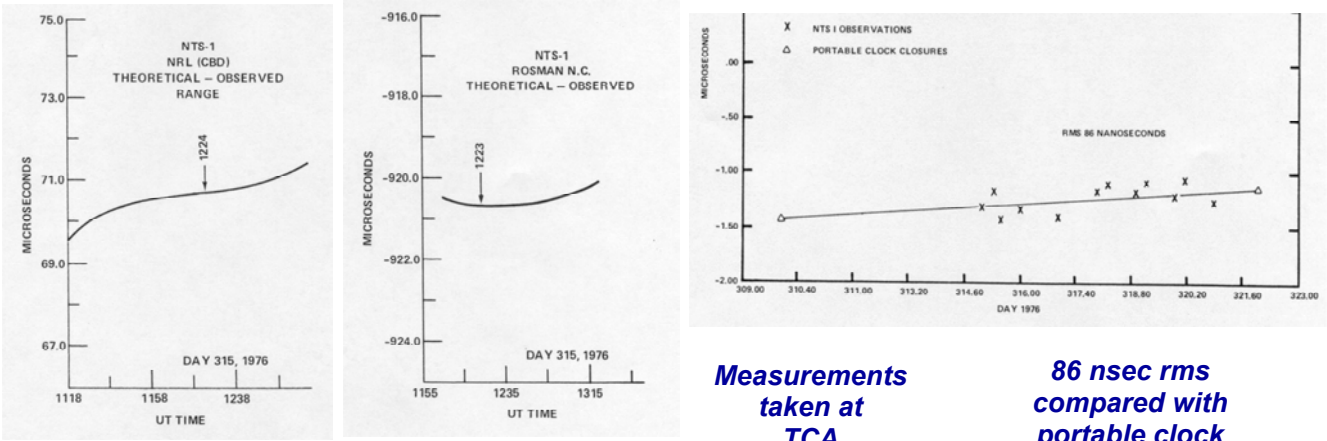


Figure 9. NTS Time Transfer Demonstration Test

Figure 10. Demonstration Test Results



Measurements
taken at
TCA

86 nsec rms
compared with
portable clock

34th Annual Precise Time and Time Interval (PTTI) Meeting



Figure 11. International Time Transfer Experiment

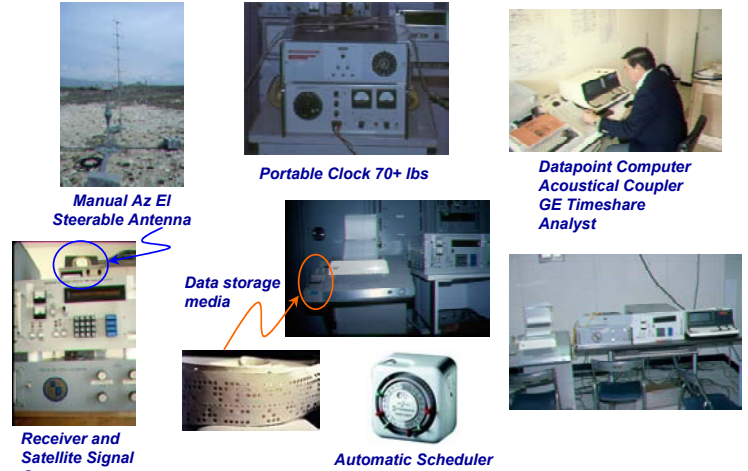


Figure 12. NTS Time Transfer Tools

Remote Site	Epoch (day 1978)	Phase Offset (microsec)	Frequency (pp10 ⁻¹¹)	RMS (nanosec)
RGO (JP)	186	-160.734	-.245	369
BIH (OP)	156	1.574	-.006	318
CERGA	130	0.995	-.049	324
IFAG	186	-10.277	-.017	377
DNM (590)	186	158.902	.329	458
RRL	303	-18.050	-.010	862
RRLM	304	-47.829	.003	998
NBS	151	-4.474	-.014	398
NRC	186	-3.716	-.005	152
USNO (MC1)	186	-.036	.000	171

Time Transfer rms 152-998nsec

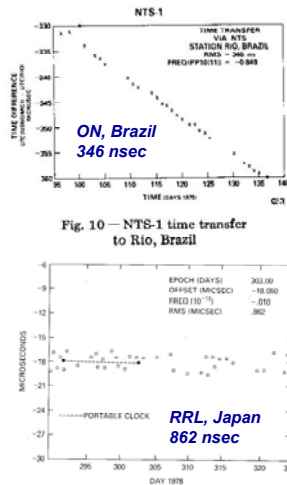


Figure 10 Time Transfer Results from RRL, Japan (1978-1981)

SUMMARY OF PORTABLE CLOCK CLOSURES VS NTS TIME TRANSFER RESULTS

STATION	DAY (1978)	PORTABLE CLOCK - NTS TIME TRANSFER (μs)
BIH	124	-.57
CERGA	117	.70
DNM	282	.09
IFAG	199	.03
NBS	221	.19
NRLM	299	-.53
RGO	115	.44
RRL	303	.13
USNO	186	.04

Figure 13. International Time Transfer Results

Figure 14. Portable Clock Results Agreement 30-700 nanoseconds

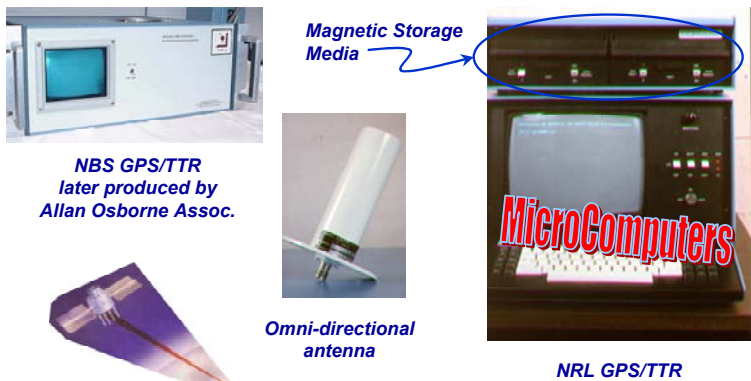


Figure 15. GPS Time Transfer Receiver Development

TIME TRANSFER BY DIRECT MEASUREMENT

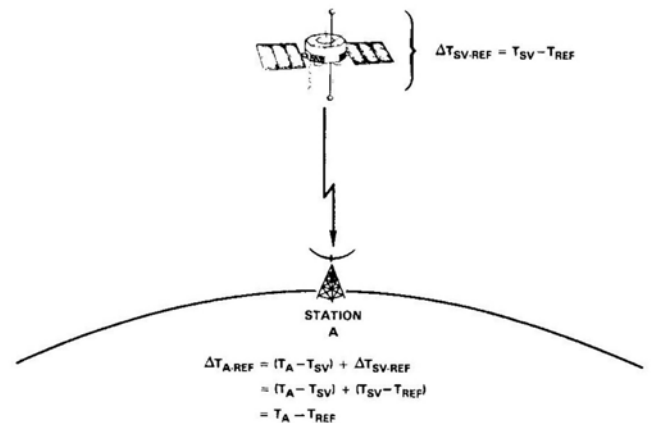


Figure 16. One-Way Time Transfer

TIME TRANSFER BY SIMULTANEOUS MEASUREMENTS

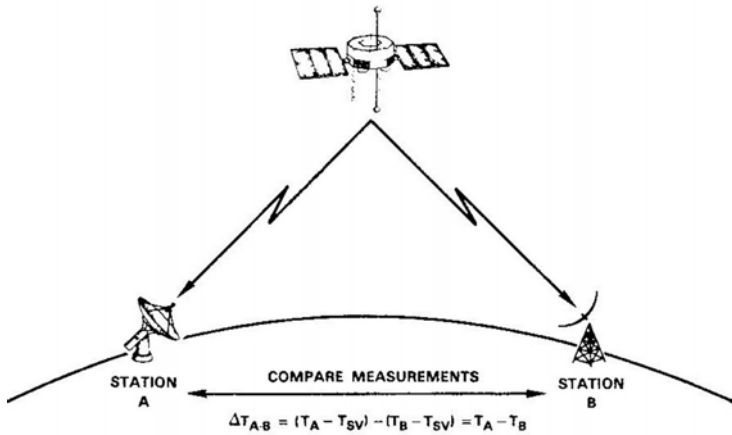


Figure 17. Common View Time Transfer



NRL GPS/TTR Calibrator



STEL 502 TTR

PARTICIPANTS
 USNO, Washington
 NBS, Colorado
 OP, Paris
 VSL, Netherlands
 PTB, Germany
 TUG, Austria

Figure 19. Remote Calibration and Time Synchronization

R-CATS METHOD

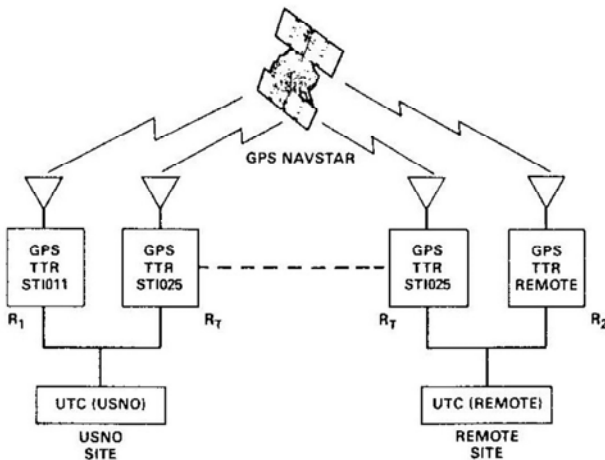


Figure 21. Calibration by Comparison

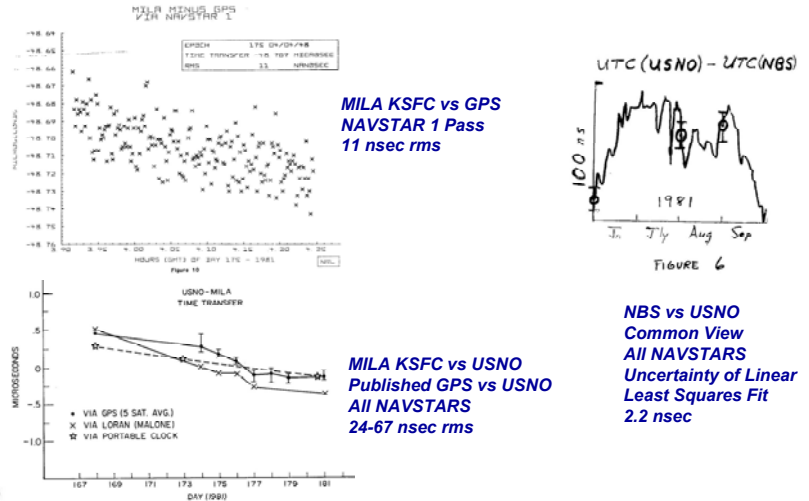


Figure 18. GPS/TTR Results

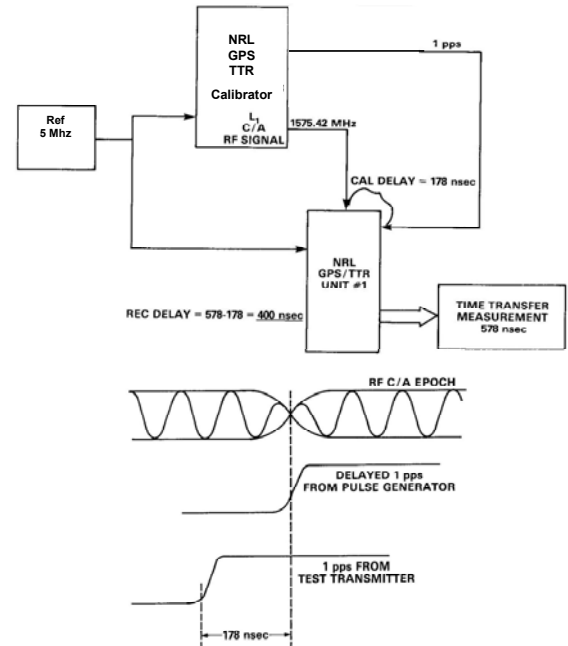


Figure 20. Calibration by Component Measurement

TABLE 3
 (STI025 - SITE) Calibration Offset

SITE	DATE	REC	NO. PTS	MEAN OFFSET (ns)	RMS (ns)
USNO	11-15-84	STI011	20	+1	7.8
OP	12-02-84	NBS06	13	-31	5.7
VSL	12-07-84	NBS01	13	4	8.9
PTB	12-12-84	NBS	14	-29	12.9
PTB1	12-12-84	NBS	16	-30	8.3
TUG	12-17-84	STI004	17	14	5.6
USNO	12-24-84	STI011	49	-9	5.6

Conclusion: Calibrations are required to maintain accurate time transfers

TABLE 4
 (STI025 - SITE) Calibration Offset

SITE	DATE	REC	NO. PTS	MEAN OFFSET (ns)	RMS (ns)
USNO	12-24-84	STI011	49	-9	5.6
USNO	02-07-85	STI011	24	-8	7.7
USNO	04-01-85	STI011	41	-10	5.9

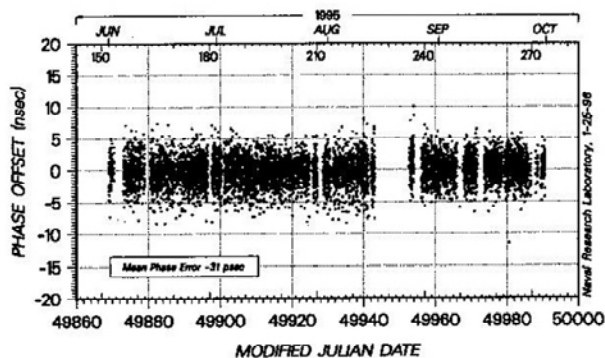
Closure of Calibration Receiver Offset

Figure 22. R-CATS Results

Linked Common View TT for MS Clocks

$$\begin{aligned}
 [\text{SVN1} - \text{WAS}] - [\text{SVN1} - \text{HAW}] &= (\text{HAW} - \text{WAS}) \\
 [\text{SVN2} - \text{HAW}] - [\text{SVN2} - \text{BEI}] &= (\text{BEI} - \text{HAW}) \\
 (\text{HAW} - \text{WAS}) + (\text{BEI} - \text{HAW}) &= (\text{BEI} - \text{WAS}) \\
 [\text{SVN3} - \text{BEI}] - [\text{SVN3} - \text{ENG}] &= (\text{ENG} - \text{BEI}) \\
 (\text{BEI} - \text{WAS}) + (\text{ENG} - \text{BEI}) &= (\text{ENG} - \text{WAS}) \\
 [\text{SVN4} - \text{ENG}] - [\text{SVN4} - \text{ASC}] &= (\text{ASC} - \text{ENG}) \\
 (\text{ENG} - \text{WAS}) + (\text{ASC} - \text{ENG}) &= (\text{ASC} - \text{WAS}) \\
 [\text{SVN5} - \text{ASC}] - [\text{SVN5} - \text{WAS}] &= (\text{WAS} - \text{ASC}) \\
 (\text{ASC} - \text{WAS}) + (\text{WAS} - \text{ASC}) &= (\text{WAS} - \text{WAS})
 \end{aligned}$$

Measurements [], Calculated ()



Mean phase error 31 psec

Continuous Coverage TT for SV Clocks

$$\begin{aligned}
 [\text{SVN1} - \text{WAS}] \\
 [\text{SVN2} - \text{HAW}] + (\text{HAW} - \text{WAS}) &= (\text{SVN2} - \text{WAS}) \\
 [\text{SVN3} - \text{BEI}] + (\text{BEI} - \text{WAS}) &= (\text{SVN3} - \text{WAS}) \\
 [\text{SVN4} - \text{ENG}] + (\text{ENG} - \text{WAS}) &= (\text{SVN4} - \text{WAS}) \\
 [\text{SVN5} - \text{ASC}] + (\text{ASC} - \text{WAS}) &= (\text{SVN5} - \text{WAS})
 \end{aligned}$$

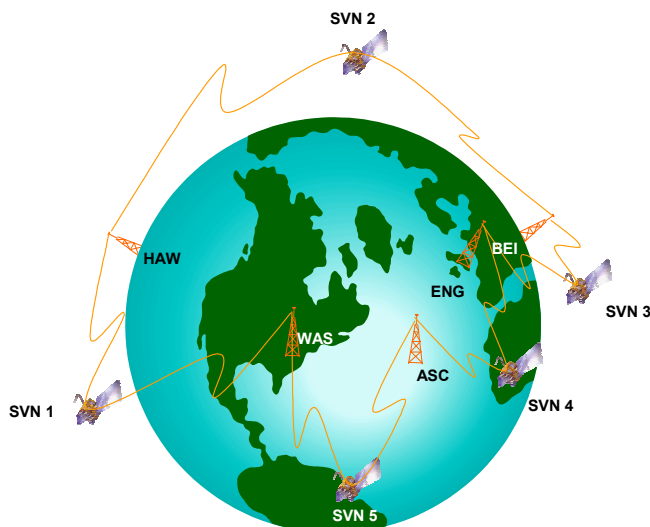
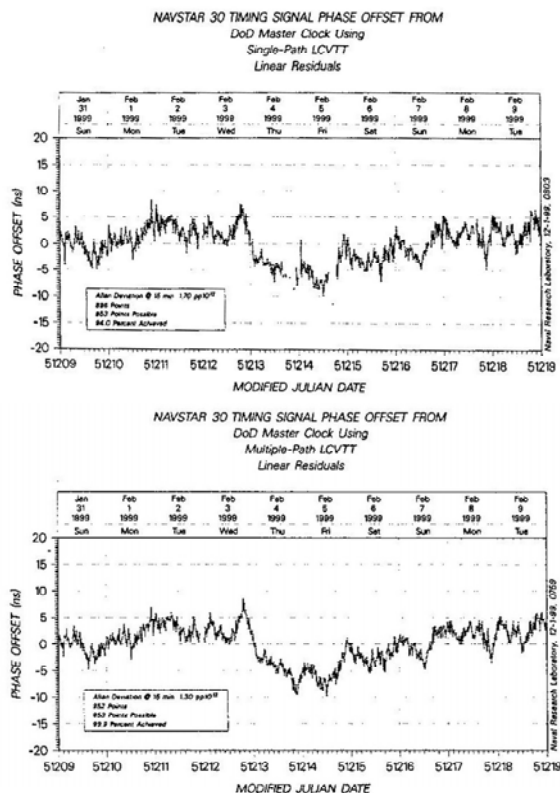
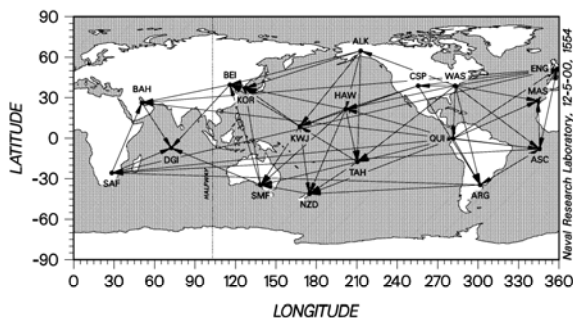


Figure 23. Linked Common View Time Transfer



COMMON-VIEW LINKS USED IN MULTIPLE-PATH LINKED COMMON-VIEW TIME TRANSFER



~10% increase in data

Reduction in noise

Figure 24. Multiple Path Linked Common View Time Transfer

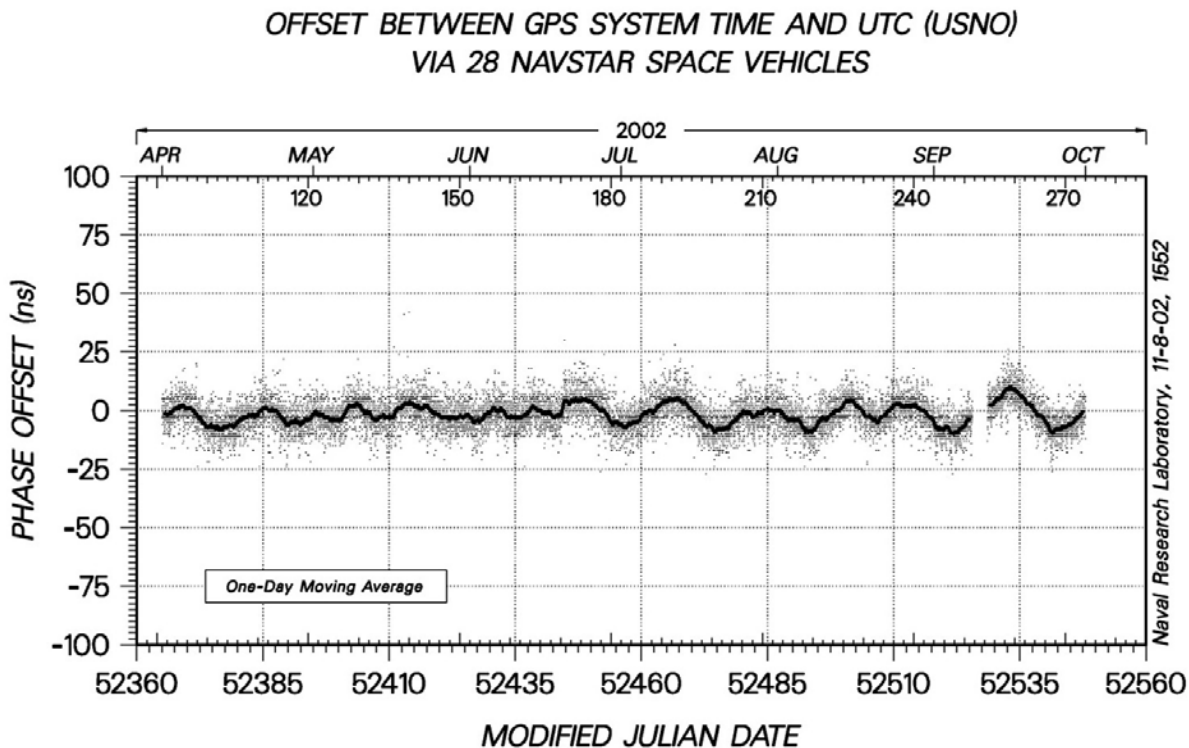


Figure 25. System Time Synchronization

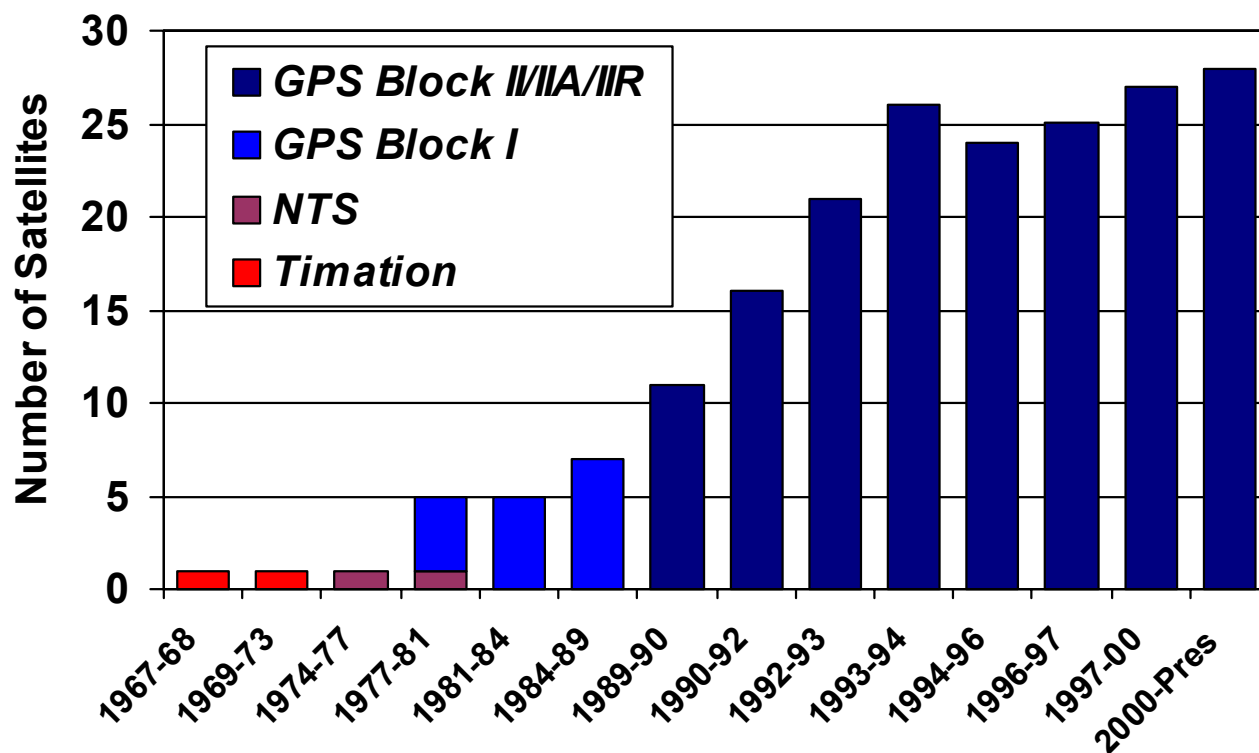


Figure 26. Satellite Availability